Deployment repeatability

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Abstract

Every time a structure is deployed, it will have a slightly different deployed shape, and this deployment-to-deployment variation is part of the shape error budget. This shape variation can be estimated by combining the variation in every deformable part, or by testing the full structure. In the latter case, evaluating the deployment repeatability builds upon the testing or analysis of deployment kinematics (Chapter 6) and adds repetition.

Introduction

Repeatability is synonymous with precision. Lake et al [1] give a simple definition of deployment precision: “The error in the final deployed shape of a structure as compared to its ground-measured shape.” This is the basis for the definition of repeatability, but a few adjustments must be made in the context of large space structures. First, large structures are not necessarily expected to match a ground-measured shape, but some predicted shape that may combine ground measurements and analysis. Second, we want to be clear that repeatability isn’t about a single final deployed position, but **the size of the envelope of statistically likely deployed shapes**.

A project may come to the characterization of repeatability having solved their problems with accuracy in an average sense, but with a concern that the ultimate deployment in space may not match the pre-flight shape prediction. Conversely, a study of repeatability may come before the study of accuracy, because a structure with millimeter-level repeatability need not undergo analysis to establish micron-level accuracy, but instead should use a shape adjustment mechanism for micron-level alignment.

Deployment repeatability contributes to thee shape error budget alongside post-deployment stability. Each of these reflect a range of actual structural shapes, but while deployment repeatability addresses the shape of the structure shortly after deployment, post-deployment stability is the variation of that deployed shape over the course of the mission. Both factors are important to a mission, but they are tested differently and generally have different root causes.

Best practices in testing

What is the ideal way of characterizing repeatability? The more directly the test can replicate actual deployment, the better, but with large space structures, it is often impossible to do a direct test without interference from gravity offload systems or the ground environment. Modeling is suitable for well-characterized parts, and stochastic modeling techniques can be used for sensitivity analysis and generating a large cohort of trials to spot unusual cases. However, deployment repeatability is inherently a nonlinear phenomenon, which makes modeling difficult without accompanying test data to use as input.

In order of preference, the following may be considered for establishing repeatability:

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1. Test the flight model from the condition of delivery through full deployment as many times as statistically required
    - Test to test variability in the gravity compensation is a problem unique to large, ultra-lightweight spacecraft structures. Depending on the level of repeatability required, characterization of the nonlinearities of the gravity compensation system may be necessary
    - Ideally, tests should be done in a relevant environment; if not, modeling may still be necessary to determine the significance of changes in e.g. friction

If full deployment testing isn't possible,

2. Test a statistically useful cohort of parts and run a Monte Carlo analysis of a model
    - In a repeating structure with a series of nominally identical parts (for example, a mast with a series of identical bays), an estimate can be made by combining the tested repeatabilities of the parts (see **Error! Reference source not found.**, **Error! Reference source not found.**)

If parts testing or computer time for a Monte Carlo analysis aren't possible,

3. Run edge cases of a model

Factors in repeatability

What contributes to the repeatability of a structure? Random effects that vary unpredictably between deployments, and progressive effects that change predictably from one deployment to the next. Some effects can reasonably be considered random in one project, but not in another.

When considering sources of deployment repeatability, it is useful to look at analogous sources of errors in measurement instruments. Examples of measurement instrument error categories are described in Figliola and Beasley [2]. Using measurement instruments as a foundation, deployment repeatability error sources for a single test article can be grouped into 4 categories:

> **Zero shift**: A test to test shift in the zero point of the expected response curve. Examples sources of zero shift frictional slip bolted joints within the structure under test or at mounting points in the GSE or material yield or failure during a test. For the purposes of this chapter, zero shift will refer to permanent changes in the structure, while reversible changes will be considered random.
>
> **Random error**: Variation in the response curve throughout all tests. Example sources could include acoustical noise in the testing environment or other environmental effects that are not well understood.
>
> **Hysteresis error**: Changes in the deployed shape based on test cycling. Example sources include material creep or test-to-test variation in the extent of deployment of the structure.
>
> **Environmental sensitivity error**: Variations in the deployed shape due to changes in the environment. Example sources include expansion or contraction of the structure due to changes

in temperature, humidity or atmospheric pressure. Many of these more obviously affect postdeployment stability, but some can alter the deployment process itself.

[Illustration of concepts to be added]

Deployment repeatability can also change from test article to test article, known as unit to unit precision error. Sources of unit to unit precision error include variations in materials, manufacturing procedures and manufacturing environment.

Zero shift errors

- Part replacement after testing
- Material damage, including damage to composite fibers and plastic deformation in metals
- Joint surface wear
- Slip in bolted connections due to launch loads

Random errors

- Free-play and friction in joints
- Internal repeatability of motors or deployment drivers
- Loss or redistribution of lubrication

Hysteresis errors

- Material creep due to time in storage and time in the space environment prior to deployment
- Number of test cycles

Environmental errors

- Randomness in spin rate and spacecraft dynamics (where these affect the deployment specifically, e.g. by biasing the initial position of a joint)
- Randomness in the environment, e.g. where the attitude is not controlled or where friction changes unreliably in vacuum or thermal conditions (where these affect the deployment, and not only postdeployment stability)
- Humidity, temperature, pressure, and airflow changes affecting ground testing

Extremely well-characterized and well-controlled satellites will have better repeatability in addition to having better post-deployment stability. In an advanced satellite, the spacecraft attitude may always be controlled to great precision, but in a Cubesat, there may be no attitude determination at all. Such a Cubesat might treat sun angle and tumbling rates as randomly distributed, and will consequently have a larger envelope of likely deployed shapes.

Many of these same effects can be found in the test equipment that is used to evaluate repeatability, and the subject of repeatability in the test fixtures themselves is addressed in "Characterization of repeatability in test equipment," below.

Test Measurements

It is important to consider what measurements would provide confidence in deployment repeatability. What shape measures are important to the mission? Ideally a structure would be tested in the same way it would be used. Consider the example of NuSTAR [2], an x-ray telescope with a 10-meter mast separating its focusing mirrors from its detectors. The aim of the mirrors on the detectors was particularly important and the telescope was relatively insensitive to errors in boom length. Three degrees of freedom would be sufficient to describe the envelope of deployment repeatability in this case, specifying the center positions of the two focused images on their two detectors and assuming that the distance between the image centers is fixed. For a case like this, an engineering model of the final metrology system could work well for testing.

In another example, the ideal measurement of a deployed parabolic RF reflector system would be a functional RF range measurement. However, this measurement would require a large RF testing range which may be unfeasible, or at least unfeasible for a series of deployment repeatability tests. When the structure cannot be measured as it will be used, a secondary measurement must be made that then needs to be related to the functional target. For a membrane RF reflector, a secondary measurement could be dot projection photogrammetry [3]. Or for RF mesh reflectors, Digital Image Correlation (DIC) with distributed targets may be necessary. As the spatial resolution of the secondary measurement decreases, larger analytical leaps are needed to translate the lower resolution repeatability measurement into an estimate of functional repeatability. This always needs to be considered when developing a deployment repeatability test.

Full structure and complex substructure testing

Testing the complete structure begins with the content of other chapters in this book: Gravity Compensation (Chapter 4) and Deployment Kinematics and Dynamics (Chapter 6). Repeating the deployment test is the simple answer to questions about repeatability, and this section discusses some concerns particular to repeatability testing.

Structural settling

It is desirable to characterize a structure both immediately after deployment and after some settling time. The structure may have better repeatability than the earlier measurement suggests, due to two effects: microlurching and material creep.

A structure with sliding joints may be subject to microlurching, where the strain energy of the structure is relieved by a series of frictional stick-slip events in the joints. Lake et al describe the effect well:

> […] it appears that structures tend to change their shape slightly after deployment to relax internal stresses built up by the deployment process. After structures have undergone a post-deployment, progressive microlurch, subsequent microlurching responses tend to be random but bounded in magnitude. The boundary of this random microlurch response is the equilibrium zone of the structure. [1]

Thermal snap (or thermal creak) [4] is one source of microlurching; microlurching can also be encouraged by intentionally exciting the structure. This early microlurching towards strain relief should

be distinguished from random or cyclic microlurching that affects postdeployment stability, long after deployment.

Material creep is particularly likely to be a factor when the structure has been stowed in a substantially different state of stress from its deployed condition. At one extreme, a pre-tensioned truss structure goes from very low stress when stowed to high stress after deployment. At the other, a strain-energy-deployed tapespring starts in a condition of very high material stress and deploys to a low-stress shape. In either case, the deployed shape can vary with stowage time and the settling time allowed after deployment.

Characterization of repeatability in test equipment

In order to have a high level of confidence in ground based repeatability measurements, the overall repeatability inherent in the test equipment and environment should be considered. Test equipment includes:

- Test article mounting fixtures
- Offload mechanisms
- Offload mounting fixtures
- Sensors
- Sensor mounting fixtures
- Structural connections between all mounting fixtures

The only aspects of test equipment repeatability unique to or especially challenging to large, ultra-lightweight structures are those related to the offloading system and the structural connections between all mounting fixtures. Offload systems are usually designed for low mass, low friction and compliance with little concern for repeatability. For smaller structures, a support frame can be used to connect the test article, sensors and other fixtures into one relatively rigid unit. For the structures considered in this handbook, this often cannot be achieved. Therefore characterizing the repeatability of all test equipment is important when quantifying the test article repeatability.

In addition to the test equipment, test-to-test changes in the testing environment may need to be considered. This can include temperature, humidity, pressure, and air flow. Concern about environmental effects on measurements is not unique to the testing of large, ultra-lightweight spacecraft structures, but their effects may show up in different ways. A key example is the cyclic airflow in the heating or air conditioning system pushing on the structure causing deformation during one measurement but not the next. Directing the air away from the test or isolating the test area with curtains can abate this, and Chapter 3 (Facilities and the Test Environment) addresses systems that require high-quality isolation.

In order to minimize test equipment repeatability error, some forethought should be given when designing the test. First of all, consider the room where the testing will take place. Often the size of the structure being tested dictates which room will be used, so a test engineer doesn't have much choice in the matter. Nonetheless, it is a good idea to make long duration measurements of the environment in the room to quantify the variations that will be seen ahead of time. The environmental variations can then be compared with thermal expansion or moisture expansion data for the materials in the test

article to see if the induced shape variations are of concern for the repeatability levels desired. Periodic changes throughout the day in temperature and/or humidity may indicate the frequency of the HVAC air handler cycle so that the airflow in the room can be further investigated.

Additionally, low frequency vibration measurements should be made in the room wherever test equipment will be mounted. For an overhead offload system, this may include the ceiling. If the levels and frequency of vibrations measured are of concern, some form of isolation should be used.

Once the environment in the room is characterized, the test fixtures can be designed to minimize the room environmental effects. As mentioned previously, in the testing of large structures the mounting fixtures for the test article, sensors and offload may be distributed around the room so that the building acts as the structural connection between all mounting fixtures. This can be problematic for repeatability tests because some or all of these fixtures may not be well constrained to the building. Then these fixtures could be inadvertently moved between tests resulting in a zero shift in the repeatability measurements. This can be addressed in two ways: either the fixtures can all be well mounted to the surrounding room or calibration measurements can be made with fixed references within the room. The first solution is self-explanatory. The second solution requires regular reference measurements with a metrology system capturing the relative location of the mounting fixtures to the fixed references. Then any relative motion can be removed from the repeatability measurements during data post-processing. For repeatability measurements on the order of XXX, photogrammetry can be used to achieve this, as shown in XXX.

Because the offload system deploys in parallel with the structure, the repeatability of the offload system alone can be difficult to quantify. For a mechanical offload system, measurements of the locations of the offload points in the deployed state with some form of metrology system can be useful to verify that similar extents of offload motion are reached from test to test. In all offload systems it is useful to verify that consistent offload forces are being applied from test-to-test. For offloading balloons this can be as simple as measuring the lift force between tests. For a mechanical system this may mean checking the spring stiffness of each offload connection or even using force sensors inline with each offload connection.

Millimeter repeatability in SAILMAST and submillimeter repeatability in GEMS

McEachen has presented two useful examples of boom testing at ATK in the 40-meter SAILMAST project [5] and the 4-meter GEMS telescope boom [6].

The GEMS boom had no allowance for on-orbit adjustment, and therefore was expected to rely entirely on ground-based demonstration of deployment accuracy and repeatability [6]. It is noteworthy that the GEMS boom was tested for repeatability as a complete structure and also evaluated for repeatability via component testing for the statistical repeatability of individual joints [7]. The component-based approach is reviewed in “Approximate estimation,” below.

The SAILMAST shape and GEMS tip position were both tracked during ground testing by a laser target tracking system.

Earlier SAILMAST testing in 2005 [8] used photogrammetry to track a set of LEDS in two dimensions, a method that was able to resolve 2.2-mm lateral displacements of a 40-meter boom. This method recalls

the strategy used by SRTM, where a constellation of lights was installed at the tip of the boom and a modified star tracker was used to track tip displacements.

Sub-milliradian repeatability in MOIRE

[This is a stand-in section for the MOIRE case study, which Dave Waller is getting through export control. The content will be largely drawn from these three papers. This standin is a trimmed copy of the abstracts of three referenced papers on MOIRE.]

The Membrane Optical Imager Real-time Exploitation (MOIRE) program, being developed by Ball Aerospace and its partners for the Defense Advanced Research Projects Agency (DARPA), seeks to enable technologies that would make orbital telescopes much lighter, more transportable and more cost-effective. MOIRE intends to design and develop a geosynchronous imager featuring a 10-meter diameter membrane optical element system at a distance 50 meters away from the spacecraft bus, with traceability to a future system with a 20-meter diameter primary optic. The program is preparing for a potential future space-based mission through large-scale, ground-based testing. Full-scale deployment testing of two petal segments combined with quarter-scale testing of a full system demonstrated feasibility of the 10-meter primary diameter design. This paper discusses the design, analysis and testing of the primary optic's structural elements. [9]

Due to the overall system size, subsystem and component level testing is necessary to capture data for incorporation into larger analysis models. Stability testing of two full-scale composite strongback segments, including in a relevant environment, was performed to correlate preliminary models of the primary diffractive optical element structure. This paper discusses the testing approach and lessons learned. [10] Another paper discusses the analysis and observed test data. [11]

Component-level testing and modeling

There are particular situations in which a project might want to incorporate component-level testing with a repeatability-oriented model: where testing is prohibitively expensive or difficult, early in the program for purposes of triange, where the design can accommodate some changes as an outcome of a sensitivity study, and where part replacements might be done without retesting of the integrated structure.

With excellent measurements of the constituent parts, modeling can capture repeatability effects. However, some caution is warranted, because modeling carries a risk of overlooking "unknown unknowns," leaving open the possibility of real-world effects that are not captured in the model because they stem from properties or situations that are not modeled. In favor of modeling, it is noted that microgravity and thermal deformation are very common subjects of modeling and both difficult and expensive to test in a large structure.

Knowing what to include in the model requires a clear understanding of what might affect repeatability. Some questions to ask include:

What can be summarized and reduced to a simpler-to-model and simpler-to-vary effects? Because the model will have to be rerun many times, simple abstractions of complex parts have great advantages. This philosophy should guide testing. It is usually better to test whole hinges for hysteretic load-

displacement paths and put this data into a computationally cheap 1-DOF abstraction of a hinge than to test the hinge's surface roughness and apply this to a computationally expensive solid contact model of the hinge. This is especially true in a structure with many repeating parts, and in an analysis that will be run many times for statistical purposes.

Is it necessary to model the deployment process, or is it sufficient to initialize the model in the fully deployed state? Some types of path-sensitive material damage might be well-captured by a fully dynamic deployment simulation. Perhaps a deployment where each joint is driven into place by a motor could be sensitive to small differences in motor controller timing. In these cases, the analyst might choose to model the entire deployment path, with knowledge of the material damage model or motor controller timing precision. On the other hand, if many repeated and environmentally representative deployment tests can be performed on the joints, it isn't necessary to model the deployment process. The test data can be integrated into each joint as part of its constitutive model, a preload on the structure, or seeded as an imperfection by a variety of methods.

Where is there friction in the structure?

What components, if any, might be swapped out between testing and flight? These components deserve a closer look at manufacturing variability, and it may be a simple modeling task to consider a statistical distribution of their properties.

What will change without the preload of gravity? In the space thermal environment? In vacuum? Joint friction can be sensitive to all of these.

Is it necessary to capture the as-built structure? If the model is only answering questions about repeatability, a highly accurate prediction of the actual shape may be unnecessary. For example, if one or two deployment tests were possible and showed excellent accuracy, the project may only be concerned with the likelihood that subsequent deployments will deviate from those tests. In this case, where there is no interest in refining the shape prediction itself, reproducing the as-built shape is probably not important.

What are the subjects of the trade or sensitivity study? Subjects for an analysis trade study could include preload in tension elements, acceptance criteria for joint surface smoothness, load levels and timing control in a driven deployment, the number of acceptable previous deployment of tapespring hinges, and any number of things that are difficult to systematically vary in physical testing.

Methods for testing joints or folded members

Single joint repeatability tests are often performed to verify new joint design concepts [12] [13] [14] or to produce data to update the joint characteristics in a larger model [15]. Another test commonly performed on joints is the linearity of the deployed joint to varying load. Uncertainty of the load in the joint at the end of deployment could be large enough that the nonlinearity in the joint response will be a significant contributor to repeatability error. If not, the joint nonlinearity would only be considered post-deployment stability error. Because of this ambiguity, it is very important to quantify the load range expected in the deployed joint and test repeatability over that range.

For elastically folding joints or rolled members, the loads expected in the stowed state are also important to quantify. The structure will most likely be under this stowed state for a long time under

varying environmental conditions resulting in large amounts of stress relaxation or creep before deployment. For these kinds of members gathering deployment repeatability data for different stow durations, possibly in different stowed environments, is recommended.

Deployment repeatability testing these relatively small components can be much easier than the greater structure because a common fixture for both the component under test and the measurement sensors often can be used. Additionally, gravity offload may not be necessary and the whole test setup may fit within available environmental chambers.

[To add: A. Carrier, J.-N. Aubrun, R. Clappier, T. Hilby, K. R. Lorell, B. Romney, L. Sokolsky, and J. Uphoff, "Development and Microdynamics Characterization of a Deployable Petal Assembly at Full Scale," Proceedings of SPIE Vol. 4850, IR Space Telescopes and Instruments, 2003.]

Approximate estimation

Simple triage for deployment repeatability can be accomplished for structures where the sources of error are well-understood and can all be categorized as "random error." McEachen [7] describes a method that is particularly well-suited to joint-dominated masts with repeating bays. It consists of a set of tests and a simplified analysis:

- Each member of a large group of joints is tested for repeatability over repeated actuations.
- The joint test results are compiled into database of joint performance, with a characteristic standard deviation of the deployed position of each degree of freedom in each joint.
- Joint errors are related linearly to bay errors via either a finite element model or a closed-form solution for the relationship between a unit error in each degree of freedom at each joint to an error in the full bay

With this database of characteristic joint repeatabilities and the relationship between joint errors and bay errors, it is possible to estimate the overall mast performance:

> Finally, the root sum of the squares of the various distortion sources (primarily joints) in each component in the relevant degrees of freedom (typically 6) was taken to be the predicted standard deviation of the system deployment repeatability. The results of this simple yet powerful algorithm was compared against hardware test results from a wide variety of deployable systems (Coilable and articulated booms, articulating hexapod structures, etc.) and found to correlate to system repeatability measurements within about a factor of two. This predictive accuracy is more than adequate for the purposes of mission planning, both in the selection of structure type, and in the allocation of alignment budgets early on in the development process. [7, p. 5]

This method is particularly cost-effective when the same joints will be used many times in one structure, or across many structures.

Simply having an order-of-magnitude estimate of a mast's repeatability may show that it is repeatable enough to skip repeated deployed testing or may show that the structure is certainly not acceptable repeatable and will require a shape adjustment mechanism. If neither of these cases apply, a more detailed assessment is called for.

[To add: basic statistical description of the error on the sample standard deviation and how to decide how many joints to test through how many repetitions of deployment [16], possibly a worked example.]

Higher-precision modeling

Stohlman and Pellegrino [15] [17] presented a study of the ATK (formerly AEC-Able) ADAM mast with a stochastic approach to certain part properties. The work particularly addresses how friction and preload in this structure can affect the range of resting positions of the mast tip when the mast is loaded as a cantilever beam. This suggests a method for bounding the possible shape envelope of a deployable structure. Every joint in the simulation can be individually loaded in the same direction and released, allowing the joint to regain static friction in a new, highly biased position. By evaluating the most extreme statically sustainable deformations of the structure, a conservative envelope for deployment repeatability can be determined.

One element of large deployable structures that is less common in small satellite is very large displacements and motions of parts. In the particular case of the ADAM mast evaluated by Stohlman and Pellegrino, the latching mechanism undergoes a large displacement between the stowed and deployed configurations, and exhibits friction throughout this range of motion. The form and motion of this latch is shown in Figure 1. Because it was critical to capture friction, and because the deployed structure includes significant tension preload in the cable diagonals, the latching mechanism had to be evaluated under a continuous load and in both directions of motion. A test setup for the latch (Figure 2) was designed to allow reversible testing of latches under tension loads.

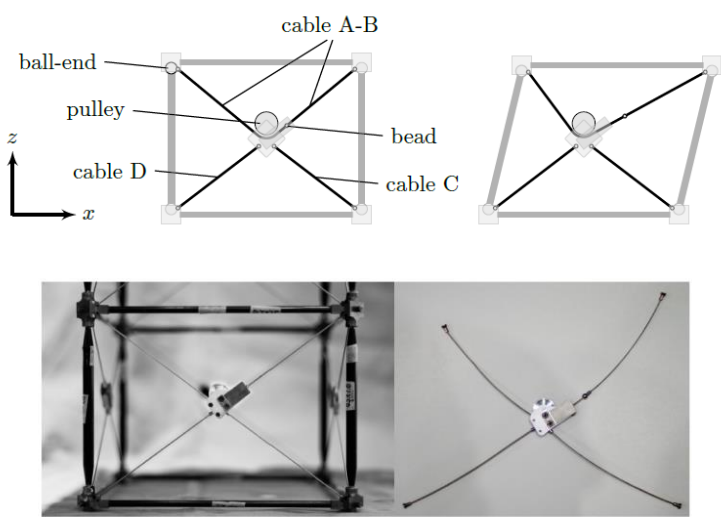

Figure 1: Assembly of diagonal cables with integral bead-capture latch.

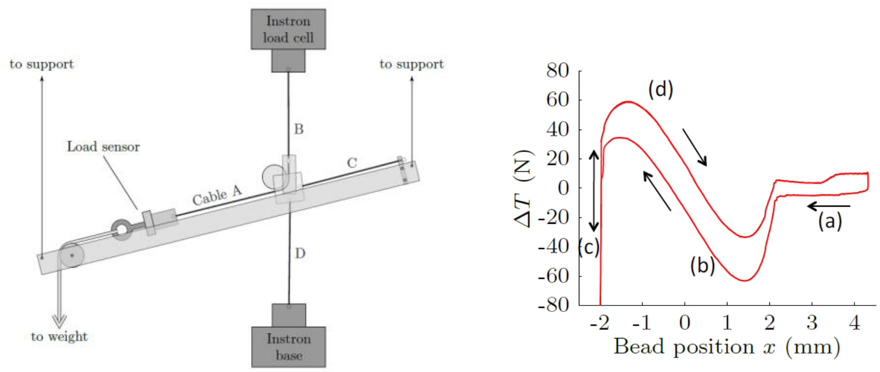

Figure 2: Experimental setup for latch testing under constant tension load and experimental latch loads for bead capture in an ADAM mast.

With this experimental setup, it was possible to capture the hysteretic latch behavior, including friction, with a single degree of freedom. This made it possible to include a complicated behavior in a relatively simple element for use in a finite element analysis, as well as isolating the effect of the latches from other sources of friction. This level of detail can provide design insight, and the data gathered to populate such a detailed finite element model is applicable to the simpler estimation method described above.

Conclusions

[Conclusions will be made into paragraphs in a later draft]

- Accuracy may be overshadowed by repeatability; similarly, both may be overshadowed by long-term post-deployment (in)stability
- Repeatability, accuracy, and stability are closely related and will touch on many of the same system requirements.
- Stability of the test fixtures and sensors should exceed repeatability of the test article
- A shape metrology and/or adjustment subsystem may drastically reduce analysis and testing demands
- (Summary of state of the art examples)

Table 1: Examples of deployable structures with characterized repeatability. Structure types and measurement goals vary between examples, so repeatabilities should not be compared directly. [Incomplete]

Structure	**Characteristic size**	**Characteristic repeatability**
GEMS mast	4 meters	96 µm
SAILMAST mast	40 meters	2 mm
MOIRE petals	3 meters	2.3 µradians

Reducing the need for repeatability testing

The NuSTAR x-ray telescope used a 10-meter-long deployable mast to separate its two arrays of focusing mirrors from its two detectors [2]. Early in the development of the system, questions were raised about

both the accuracy of the deployed shape during gravity-compensated tests and about deployment repeatability. At this point, there were two possible paths: testing to strictly bound the repeatability, combined with both testing and modeling to increase confidence in shape accuracy; or a metrology and adjustment system to correct for any errors.

The NuSTAR project opted for a metrology and adjustment system, which had many advantages for the project and few disadvantages. Because a three-degree-of-freedom alignment between the root and tip of the mast was the only adjustment required, a laser metrology system and angle adjustment mechanism were sufficient. The mast deployment was ultimately tested only a few times before flight, and alignment requirements were met during commissioning on orbit. In addition to greatly reducing the requirements for the mast's accuracy and repeatability, the mechanism was used to remove misalignments from thermal distortion of the mast throughout the course of the mission [18].

Where a post-deployment adjustment is feasible, it can greatly reduce the need for deployment testing. The disadvantages of such a system are typically added complexity, mass, volume, and commissioning time. The balance between these factors is very particular to the project.

Further reading

A number of additional studies may be of interest to the reader.

Frank and Dumm used a granite-table-mounted test setup to evaluate the deployment repeatability of a tripod truss with strain-energy-deployed tapespring hinges. The deployment repeatability was found to be in the hundreds of microns over 2.9 meters. [19]

Hysteresis in composites is a subject far outside the scope of this book; a body of literature exists even in the subtopic of tapespring hinges [20] [12] [19]. Temperature-dependent relaxation and creep, plastic deformation, and progressive damage may each be significant, and may also be amenable to analysis.

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